

# Cosmological Implications of Two Conflicting Deuterium Abundances

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## Abstract

Constraints on big bang nucleosynthesis (BBN) and on cosmological parameters from conflicting deuterium observations in different high red-shift QSO systems are discussed. The high deuterium observations by Carswell *et al.*, Songaila *et al.*, and Rugers & Hogan is consistent with  $^4\text{He}$  and  $^7\text{Li}$  observations and Standard BBN ( $N_\nu = 3$ ) and allows  $N_\nu \leq 3.6$  at 95% C.L., but is inconsistent with local observations of D and  $^3\text{He}$  in the context of conventional theories of stellar and Galactic evolution. In contrast, the low deuterium observations by Tytler, Fan & Burles and Burles & Tytler are consistent with the constraints from local Galactic observations, but require  $N_\nu = 1.9 \pm 0.3$  at 68% C.L., excluding Standard BBN at 99.9% C.L., unless the systematic uncertainties in the  $^4\text{He}$  observations have been underestimated by a large amount. The high and low primordial deuterium abundances imply, respectively,  $\Omega_B h^2 = 0.005 - 0.01$  and  $\Omega_B h^2 = 0.02 - 0.03$  at 95% C.L. When combined with the high baryon fraction inferred from x-ray observations of rich clusters, the corresponding total mass densities (for  $50 \leq H_0 \leq 90$ ) are  $\Omega_M = 0.05 - 0.20$  and  $\Omega_M = 0.2 - 0.7$ , respectively (95% C.L.) The range of  $\Omega_M$  corresponding to high D is in conflict with dynamical constraints ( $\Omega_M \geq 0.2 - 0.3$ ) and with the shape parameter constraint ( $\Gamma = \Omega_M h = 0.25 \pm 0.05$ ) from large scale structure formation in CDM and  $\Lambda\text{CDM}$  models.

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## I. INTRODUCTION

Among the light nuclides synthesized during the early evolution of the universe, deuterium is unique in its sensitivity to the universal density of baryons and in the simplicity of its galactic evolution. As gas is incorporated into stars and the heavy elements are synthesized, D is only destroyed [1] so that any D abundance inferred from observations provides a *lower* bound to its primordial value.<sup>1</sup> Unfortunately, an *upper* bound to the primordial D abundance is more uncertain, depending on the evolutionary history of the matter being observed. Thus, although estimates of the D abundance in the presolar nebula [2,3] and in the local interstellar medium (ISM) [4,5] provide interesting lower bounds to primordial D [ $X_{2P} \geq X_{2\odot} = (3.6 \pm 1.3) \times 10^{-5}$ ,  $X_{2P} \geq X_{2\text{ISM}} = (2.2 \pm 0.3) \times 10^{-5}$ , where the H mass fraction has been taken to be  $X_{\odot} = X_{\text{ISM}} = 0.70 \pm 0.01$ ], upper bounds are more model dependent (see, for example, Ref. [6–8,3,9]). For this reason, observations of D in (nearly) unevolved systems (high red-shift, low metallicity QSO absorbers) have been eagerly anticipated. If, indeed,  $X_{2P} \sim X_{2\text{QSO}}$ , then because of the sensitivity of the D abundance to the nucleon abundance ( $\eta = n_B/n_\gamma$ ; the ratio of the present baryon density to the critical density is  $\Omega_B h^2 = 0.0037\eta_{10}$ , where the Hubble parameter is  $H_0 = 100h$  km/s/Mpc and  $\eta_{10} = 10^{10}\eta$ ), a measurement of  $(D/H)_{\text{QSO}}$  to  $\sim 30\%$  accuracy will lead to a determination of  $\eta$  to  $\sim 20\%$  accuracy. Armed with  $\eta$ , reasonably accurate predictions of the primordial abundances of  $^3\text{He}$ ,  $^4\text{He}$ , and  $^7\text{Li}$  will follow (see, for example, Ref. [9]). For example, for  $1.5 < \eta_{10} < 10$ , a 20% uncertainty in  $\eta_{10}$  will lead to an uncertainty in the predicted  $^4\text{He}$  mass fraction which ranges from  $\sim 0.003$  (at low  $\eta_{10}$ ) to  $\sim 0.002$  (at high  $\eta_{10}$ ). Deuterium is the ideal baryometer.

In the last two years, observations of D in high red-shift, low metallicity QSO absorbers

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<sup>1</sup>  $X_{2P} > X_{2\text{OBS}}$ , where the D mass fraction is  $X_2 = 2X n_D/n_H$ ;  $X$  is the hydrogen mass fraction, and  $n_x$  is the number density for nuclide  $x$ ; the subscript P is for the primordial abundance. As an estimate of the primordial value  $X_P = 1 - Y_P$ , we will adopt  $X_P = 0.76 \pm 0.01$ . In this paper we quote  $1\sigma$  uncertainties unless otherwise indicated.

have begun to appear in the published literature [10–14]. The first observations of D in absorption against Q0014+813 [10–12] suggested a surprisingly high abundance [for our quantitative comparisons we will adopt the recent reanalysis by Rugers and Hogan:  $D/H = (1.9 \pm 0.4) \times 10^{-4}$ ,  $X_2 = (2.9 \pm 0.6) \times 10^{-4}$ ], roughly an order of magnitude larger than the presolar or ISM values ( $X_{2\text{QSO}}/X_{2\text{ISM}} \sim 8 \pm 3$ ,  $X_{2\text{QSO}}/X_{2\odot} \sim 13 \pm 3$ ). As such efficient D destruction in the Galaxy is not expected [6–8,3,15] it has been suggested that the feature identified as D in Q0014+813 might be a hydrogen interloper [16]. However, the Rugers-Hogan reanalysis argues against this possibility. Further, recent papers [17,18] present evidence for D absorption in front of two other QSOs (Q0420-388 and BR1202-0725, respectively) which, if the identifications are correct, suggest  $D/H \geq 2 \times 10^{-5}$  and  $D/H \leq 1.5 \times 10^{-4}$ , respectively. Although puzzling from the point of view of chemical evolution in the Galaxy, the high D abundance points towards a low baryon density ( $\eta_{10} \sim 2$ ) which is consistent with the predicted and observed (inferred) primordial abundances of  $^4\text{He}$  and  $^7\text{Li}$  [16,19]. As we shall see, however, this low baryon density ( $\Omega_{\text{B}}h^2 \sim 0.007$ ) is in conflict with determinations of the total mass density and the baryon fraction inferred from x-ray observations of rich clusters.

In contrast, from recent observations, Tytler, Fan, and Burles [13] and Burles and Tytler [14] derive a low D abundance:  $(D/H) = [2.3 \pm 0.3 \text{ (stat)} \pm 0.3 \text{ (sys)}] \times 10^{-5}$  towards the QSO1937-1009 [13] and  $(D/H) = [2.5^{+0.5}_{-0.4} \text{ (stat)} \pm 0.4^{+0.4}_{-0.3} \text{ (sys)}] \times 10^{-5}$  towards the QSO1009+2956 [14]. We have combined their two results to obtain  $(D/H)_{\text{QSO}} = (2.4 \pm 0.5) \times 10^{-5}$ ;  $X_{2\text{QSO}} = (3.6 \pm 0.8) \times 10^{-5}$ . Although marginally larger than ISM deuterium ( $X_{2\text{QSO}}/X_{2\text{ISM}} = 1.6 \pm 0.4$ ), the low D abundance is not very different from the presolar value ( $X_{2\text{QSO}}/X_{2\odot} = 1.0 \pm 0.4$ ), suggesting that even though the absorbers are at high redshift ( $z_{\text{abs}} = 3.572$  and  $2.504$ ) and have very low metallicity ( $\sim 10^{-3}$  solar), some D may have already been destroyed ( $X_{2\text{P}} \geq X_{2\text{QSO}}$ ). If indeed  $X_{2\text{P}} \sim X_{2\text{QSO}}$  (no significant D destruction), then the problems for BBN identified by Hata *et al.* [19], which were based on  $X_{2\text{P}}$  inferred from solar system observations of D and  $^3\text{He}$ , persist. The higher baryon density suggested by the low D result is, however, in agreement with the x-ray cluster data

(but still supports a low density universe).

It is hoped that future observations of D in other high red-shift, low metallicity QSO absorbers will resolve the current dichotomy between the high D result for Q0014+813 on the one hand [10–12] and the low D results for Q1937-1009 and Q1009+2956 on the other [13,14]. Here, we explore the implications for cosmology (the baryon density), for the primordial abundances of the other light nuclides ( $^4\text{He}$  and  $^7\text{Li}$ ), and for particle physics (bounds to the effective number of equivalent light neutrinos,  $N_\nu$ ), of the high D abundance and contrast them with those for the low D abundance.

## II. PRIMORDIAL D AND BBN

If  $(\text{D}/\text{H})_{\text{P}}$  is fixed, standard big bang nucleosynthesis (SBBN: homogeneous,  $N_\nu = 3$ , the neutron life time  $\tau_n = 887 \pm 2$  s, etc) can be used to predict the primordial abundances of the other light nuclides and determine the present baryon density. In Fig. 1 the SBBN predicted abundances of  $^4\text{He}$  (mass fraction  $Y$ ), D ( $y_2 = \text{D}/\text{H}$ ), and  $^7\text{Li}$  ( $y_7 = ^7\text{Li}/\text{H}$ ) are shown as a function of the nucleon to photon ratio  $\eta$  for  $1 \leq \eta_{10} \leq 10$ . Convoluting the SBBN predictions (including uncertainties estimated by the Monte Carlo method of Ref [20]) with the high D and low D results constrains  $\eta$  and leads to predictions of  $Y$  and  $y_7$  as may be seen in Fig. 1. Also shown in Fig. 1 are the 68 and 95% C.L. contours for the overlap between the inferred primordial abundances of  $^4\text{He}$  [ $Y_{\text{P}} = 0.232 \pm 0.003$  (stat)  $\pm 0.005$  (sys)] and  $^7\text{Li}$  [ $\log y_7 = -9.8 \pm 0.2$  (sys)  $\pm 0.3$  (depletion/creation)]<sup>2</sup> and the BBN predictions. When using the low D value we must ensure that consistency with the ISM (and solar system) value is maintained ( $X_{2\text{P}} \geq X_{2\text{ISM}}$ ;  $X_{2\text{P}} \geq X_{2\odot}$ ). In Fig. 2 we show the SBBN likelihood distribution (solid curve) for the low D result [ $\log y_2^{\text{QSO}} = -4.62 \pm 0.05 \pm 0.06$ ;  $y_2^{\text{QSO}} = (2.4 \pm 0.5) \times 10^{-5}$ ]. Requiring that the QSO D abundance be no smaller than

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<sup>2</sup> The statistical uncertainty in  $^4\text{He}$  is assumed to be Gaussian, while the systematic uncertainties in  $^4\text{He}$  and  $^7\text{Li}$  and the uncertainty in  $^7\text{Li}$  depletion/creation are treated as flat (top hat) distributions. The statistical uncertainty in  $y_7$  is small compared to the systematic and depletion/creation uncertainties.

the ISM D abundance [ $y_2^{\text{QSO}} \geq y_2^{\text{ISM}} = (1.6 \pm 0.2) \times 10^{-5}$ ], modifies the distribution to the dotted curve in Fig. 2, very slightly truncating the lower end of the  $y_2$  distribution [ $y_2^{\text{QSO/ISM}} = (2.4 \pm 0.5) \times 10^{-5}$ ]. It is this latter distribution which we will use in our comparisons. If, further, we also require that the QSO D abundance exceeds that inferred for the presolar nebula [ $y_{2\odot} = (2.6 \pm 0.9) \times 10^{-5}$ ] [2], the distribution (dashed curve in Fig. 2) is slightly shifted to higher values [ $y_2^{\text{QSO/ISM}/\odot} = (2.6 \pm 0.5) \times 10^{-5}$ ]. Given that the solar system data may be subject to different systematic errors than those associated with the QSO and ISM absorption observations, we will limit our analysis to those which follow from the marginally less restrictive QSO/ISM constraint. The resulting SBBN constraints on  $\eta$ ,  $\Omega_B h^2$ ,  $N_\nu$ ,  $Y$ , and  $y_7$  which follow from the high and low-QSO/ISM D abundances are summarized in Table I along with, for comparison, the previous Hata *et al.* results [9] which utilized solar system D and  $^3\text{He}$  abundances. Fig. 3 shows the likelihood distributions for  $\eta$  for high and low primordial deuterium.

A glance at Fig. 1 reveals the well-known result [21] that high-D is consistent with the primordial  $^4\text{He}$  abundance inferred from HII region data. In Fig. 4 is shown the SBBN predicted  $^4\text{He}$  mass fractions corresponding to the two deuterium values. It is clear from Figs. 1 and 4 that, in the absence of large systematic errors in  $^4\text{He}$ , the observed  $^4\text{He}$  abundance favors high-D and is inconsistent with low-D.

In Fig. 5 we compare the SBBN predictions of  $^7\text{Li}$  for high and low deuterium with that inferred from observations of the Pop II halo stars [22–25]. As is clear from Figs. 1 and 5, and Table I, consistency with lithium is achieved for both high and low D. Notice, however, that while the high-D (low  $\eta$ ) overlap with SBBN bounds stellar destruction/dilution of  $^7\text{Li}$  ( $y_7 \leq 3.0 \times 10^{-10}$ ;  $\log y_7 \leq -9.5$ ), the low-D (high  $\eta$ ) overlap actually requires some modest destruction/dilution ( $3.0 \leq 10^{10} y_7 \leq 7.8$ ;  $-9.5 \leq \log y_7 \leq -9.1$ ).

Finally, we turn to  $^3\text{He}$ , whose post-BBN evolution is model (galactic chemical evolution) dependent. However, since production of  $^3\text{He}$  by low mass stars can only increase the  $^3\text{He}$  abundance, observations of D and  $^3\text{He}$  constrain the primordial D and  $^3\text{He}$  abundances

[26,27,3,9]. For any chemical evolution history the observed and primordial abundances of D and  $^3\text{He}$  may be related through one parameter  $g_3$ , the effective  $^3\text{He}$  stellar survival fraction, which contains all the stellar and galactic evolution uncertainties [26,3,9]. While for a single generation of stars  $g_3 \geq 0.25$  [28,29], many specific evolution models suggest  $g_3 \geq 0.5$  [8,30,29]. Following Ref. [9] we show in Fig. 6 the allowed regions in the  $y_{3\text{P}}-y_{2\text{P}}$  plane inferred from SBBN and the high and low deuterium abundances. Although the low-D data is entirely consistent with the galactic evolution of D and  $^3\text{He}$ , the high-D data requires a surprisingly small value of  $g_3$  ( $\leq 0.10$  at 95% C.L.) for consistency. Indeed, the high-D data suggests that more than 90% of the present ISM has been cycled through stars (since D would have to have been destroyed by a factor of  $\sim 10$ ). With such efficient processing of gas through stars, the low metallicity of the ISM is a challenge to galactic chemical evolution models [6,7].

### III. SBBN AND $N_\nu$

From the discussion above it is clear that high primordial D is entirely consistent with the predictions of SBBN and the observed abundances of  $^4\text{He}$  and  $^7\text{Li}$ . For low primordial D there is a significant tension between the predictions of SBBN and the inferred primordial abundance of  $^4\text{He}$ . If we allow  $N_\nu$ , the equivalent number of light neutrinos, to depart from the SBBN value  $N_\nu = 3$ , we may use the combined D,  $^4\text{He}$ , and  $^7\text{Li}$  data to find the best  $N_\nu$ . Fig. 7 shows the  $N_\nu$  likelihood distributions for high and low (QSO/ISM) D; for comparison we also show the distribution derived from solar system D and  $^3\text{He}$  with  $g_3 = 0.25 - 0.50$  [9]. Of course, it is always possible that  $Y_{\text{P}}$ , inferred from nearly primordial (low metallicity) extragalactic HII regions [31–33], has been underestimated due to systematic errors. Although such uncertainties (ionization corrections, collisional excitation corrections, corrections for dust, corrections for stellar absorption, etc.) could either decrease or increase the inferred value ( $Y_{\text{P}} = 0.232 \pm 0.003$ ), recent work has emphasized those corrections which might increase  $Y_{\text{P}}$  [34,35]. If we write  $Y_{\text{P}} = 0.232 \pm 0.003 + \Delta Y_{\text{sys}}$  (where  $\Delta Y_{\text{sys}} \geq 0$ ), then

there is a direct relation between  $\Delta Y_{\text{sys}}$  and  $N_\nu$ , which we show for high and low deuterium in Fig. 8. For  $\Delta Y_{\text{sys}} \leq 0.009$ , high-D and SBBN are consistent ( $N_\nu = 3$ ), but, if  $\Delta Y_{\text{sys}}$  is larger,  $N_\nu \geq 3$  would be required. In contrast, SBBN and low-D are inconsistent unless  $\Delta Y_{\text{sys}} \geq 0.011$ .

#### IV. $\Omega_B$ AND $\Omega_M$

Either choice of high or low deuterium leads, through SBBN, to reasonably tight constraints on the present ratio of nucleons to photons (see Fig. 1 and Table I), thus bounding the present universal density of baryons  $\rho_B$ . Comparing  $\rho_B$  to the critical density  $\rho_c$ , we have

$$\Omega_B = \frac{\rho_B}{\rho_c} = 3.66 \times 10^{-3} \eta_{10} h^{-2}. \quad (1)$$

In Fig. 9 we show the  $\Omega_B$  vs.  $H_0$  relation, where the two bands correspond to the 68 and 95% C.L. ranges for  $\eta_{10}$  allowed by the QSO D abundances (see Table I). Also shown in Fig. 9 is an estimate of the luminous baryons identified by observations in the radio, optical, ultra-violet, and x-ray parts of the spectrum [36],

$$\Omega_{\text{LUM}} = 0.004 + 0.0007 h^{-3/2}. \quad (2)$$

Over the entire range of  $H_0$ ,  $\Omega_B \geq \Omega_{\text{LUM}}$ , suggesting the presence of dark baryons. As a minimum estimate of the total density (baryons plus non-baryonic dark matter) inferred from the dynamics of groups, clusters, etc., we have adopted  $\Omega_{\text{DYN}} \geq 0.2$  [37–39] (although others have suggested  $\Omega_{\text{DYN}} \gtrsim 0.3$  [40]). As can be seen from Fig. 9, unless  $H_0$  is very small (and D is very low),  $\Omega_{\text{DYN}} \geq \Omega_B$ , providing support for the presence of non-baryonic dark matter.

X-ray emission from the hot (baryonic) gas in rich clusters of galaxies offers a valuable probe of the fraction of the total mass in the universe contributed by baryons. Although relatively rare, such large mass concentrations are expected to provide a fair sample of  $f_B = \Omega_B/\Omega_M$ , where  $\Omega_M$  is the total matter density parameter [41–43]. For clusters,  $f_B =$

$M_B/M_{\text{TOT}} > M_{\text{HG}}/M_{\text{TOT}}$ , where  $M_{\text{HG}}$  is the mass of the x-ray emitting hot gas in the cluster and  $M_{\text{TOT}}$  is the total mass which determines the cluster binding. It is conventional to write  $f_{\text{HG}} = f_{50}h_{50}^{-3/2}$ , where  $h_{50} = H_0/50 \text{ km/s/Mpc}$ , so that

$$\Omega_M h_{50}^{1/2} < 0.0146\eta_{10}/f_{50}. \quad (3)$$

The inequality in (3) arises from the neglect of the baryons in the galaxies of the cluster; their inclusion would reduce the upper bound on  $\Omega_M$  by  $\lesssim 5\text{--}20\%$  (depending on  $H_0$ ). However, since the presence of other (dark) baryons (e.g., Machos) cannot be excluded observationally and may be large [44], the cluster data is best utilized to provide an *upper* bound to  $\Omega_M$ . Thus, in our subsequent analysis we shall employ x-ray data and BBN to evaluate the right hand side of Eqn. 3 which we will use to provide an upper bound to  $\Omega_M$  (as a function of  $H_0$ ).

The surprise provided by x-ray observations of rich clusters has been the relatively large baryon fraction ( $f_{50} \geq 0.1 - 0.2$ ) which, when coupled to the relatively low upper bound on  $\eta_{10}$  from BBN, has led to the ‘‘X-Ray Cluster Baryon Catastrophe’’ [41,42,45]:  $\Omega_M < 1$  unless  $H_0$  is very small.

Following the recent analysis of Evrard *et al.* [43] and Evrard [46], we adopt  $f_{50} = 0.20 \pm 0.03$ , and use this and the bounds on  $\eta_{10}$  from high and low D (see Table I) to constrain the  $\Omega_M$  vs.  $H_0$  relation (Eqn. 3) in Fig. 10. We have allowed  $H_0$  to remain unconstrained although we believe that recent data suggest  $H_0 = 70 \pm 15 \text{ km/s/Mpc}$  ( $h = 0.7 \pm 0.15$  and  $h_{50} = 1.4 \pm 0.3$ ). The x-ray cluster constraints require low  $\Omega_M$ , excluding the preferred Einstein-de Sitter value of  $\Omega_M = 1$  unless  $f_{50}$  and/or  $H_0$  is much smaller than data indicate.

Further evidence for low  $\Omega_M$  in the context of cold dark matter models (CDM) comes from large scale structure constraints on the shape parameter (see, for example, [47]):  $\Gamma = \Omega_M h = 0.25 \pm 0.05$ . Since the popular inflationary paradigm suggests that the 3-space curvature may vanish, evidence in favor of low  $\Omega_M$  has led to consideration of an alternative cosmology with a non-vanishing cosmological constant ( $\Lambda$ ) such that  $\Omega_{\text{TOT}} = \Omega_M + \Omega_\Lambda = 1$  (see, for example, [45]). Such  $\Lambda$  cold dark matter models ( $\Lambda\text{CDM}$ ) provide the additional



benefit of helping to resolve the “age problem” (for the same value of  $\Omega_M$ , and fixed  $H_0$ , a  $\Lambda$ CDM universe is older than the corresponding CDM universe). In Figs. 11 and 12 we show (at 68% C.L.) the regions in the  $H_0$ – $\Omega_M$  plane consistent with the x-ray/BBN constraints (for high and low D) and with the shape parameter ( $\Gamma$ ). Also shown is the  $\Omega_M$ – $H_0$  relation for two choices of the present age of the universe ( $t_0 = 12$  and 15 Gyr) along with the dynamically inferred lower bound to the mass density ( $\Omega_{\text{DYN}}$ ). In both cases (CDM and  $\Lambda$ CDM), the low-D, high- $\eta_{10}$  choice is preferred over the high-D, low- $\eta_{10}$  result.

A third popular cosmology is the mixed, hot plus cold dark matter model (HCDM; see for example, [48–50]). In its standard version it is assumed that  $\Omega_M = 1$ , but that  $\sim 20 - 30\%$  of  $\Omega_M$  is in hot dark matter (e.g., neutrinos with mass of 1 – 10 eV) which is relatively unclustered on large scales. The shape parameter constraint is not relevant to constraining the HCDM model, but the requirement that  $\Omega_{\text{TOT}} = 1$  exacerbates the x-ray cluster baryon catastrophe [41–43,45] and the age problem. Even if all HDM could be excluded from x-ray clusters [51], which seems unlikely [52],  $\Omega_M \gtrsim 1 - \Omega_{\text{HDM}}$ . Coupled with the upper bound from the x-ray cluster data,  $\Omega_M < 0.7$ , this requires  $\Omega_{\text{HDM}} \gtrsim 0.3$ , nearly closing the preferred window ( $0.2 \lesssim \Omega_{\text{HDM}} \lesssim 0.3$ ) on HCDM models.

## V. DISCUSSION

A determination of the deuterium abundance in a nearly uncontaminated environment such as that provided by high redshift, low metallicity QSO absorption clouds could be a key to testing the consistency of primordial nucleosynthesis in the standard, hot, big bang cosmology, to pinning down the universal density of baryons, and to constraining physics beyond the standard model of particle physics. Such data is beginning to be acquired but, at present, the observational situation is in conflict. On the one hand there is evidence in favor of high D [11,10,12,18,17]:  $(D/H) \sim 2 \times 10^{-4}$ . In contrast, Tytler, Fan, & Burles [13] and Burles & Tytler [14] find evidence for low D:  $(D/H) \sim 2 \times 10^{-5}$ . If the former, high-D values are correct, it is surprising that Tytler, Fan, & Burles and Burles & Tytler fail to

find such a large abundance in their high redshift ( $z = 3.57$  and  $2.50$ ), very low metallicity ( $Z/Z_\odot \sim 10^{-3}$ ) absorbers; high  $z$  and low  $Z$  argue against an order of magnitude destruction of primordial D. If, instead, the low D result is correct, such weak D-absorption might often go unnoticed and the high-D cases might be accidental interlopers. Based on velocity information Rugers and Hogan [12] argue against this possibility which, if more high-D cases are found, will become increasingly unlikely. Presumably, the present confused situation will be clarified by the acquisition of more data. Here, we have considered separately the consequences for cosmology and particle physics of the high-D and low-D data.

For the high-D case, SBBN ( $N_\nu = 3$ ) is consistent with the inferred primordial abundances of D,  $^4\text{He}$ , and  $^7\text{Li}$  provided that the baryon density is small (see Table I and Figs. 1, 3, 4, 5, 7, and 8). However, for consistency with the solar system and/or present interstellar D abundances, such a large primordial D abundance requires very efficient D destruction. The low baryon density which corresponds to high-D still leaves room for dark baryons and reinforces the case for non-baryonic dark matter (see Fig. 9). However, when combined with the x-ray cluster data, low  $\Omega_B$  and high  $f_{\text{HG}}$  suggest a very low density universe ( $\Omega_M \lesssim 0.21$  for  $H_0 \geq 50$  km/s/Mpc; see Fig. 10). The conflict between the upper bound on  $\Omega_M$  and the evidence for a lower bound  $\Omega_{\text{DYN}} \gtrsim 0.2 - 0.3$  argue against high-D and low  $\eta_{10}$  (see Figs. 11 and 12). Such a low value for  $\Omega_M$  is also in conflict with the constraint from the shape parameter  $\Gamma$  (see Figs. 11 and 12). These problems persist even allowing for a non-vanishing cosmological constant (which could resolve the age-expansion rate problem). See Figs. 11 and 12.

In contrast, the low-D case leads to severe tension between the SBBN prediction and the inferred primordial abundance of  $^4\text{He}$  (see Figs. 1, 4, and 5). This stress on SBBN can be relieved if the primordial helium mass fraction, derived from observations of low metallicity HII regions, is in error — due, perhaps, to unaccounted systematic effects — by an amount  $\Delta Y_{\text{sys}} \geq 0.011$  (see Fig. 8).

Alternatively, this conflict could be evidence of “new physics” [53] ( $N_\nu \neq 3$ ; see Figs. 7 and 8). The best fit between predictions and observations with low D is for  $N_\nu = 1.9 \pm 0.3$ .

One way to alter standard BBN is to change the physics of the neutrino sector. For example, many models predict the existence of sterile neutrinos, which interact only by mixing with the ordinary neutrinos. Such sterile neutrinos would not contribute significantly to the number of effective neutrinos ( $2.991 \pm 0.016$ ) inferred from the Z line-shape [54], but could be produced cosmologically for a wide range of masses and mixings [55]. However, they only increase  $N_\nu$ , exacerbating the discrepancy.

Another possibility arises if  $\nu_\tau$  has a mass in the range  $10 \text{ MeV} \lesssim M_{\nu_\tau} \leq 24 \text{ MeV}$  (the upper limit is the recent result from ALEPH [56]). In this case BBN production of  ${}^4\text{He}$  can be either increased or decreased (relative to the standard case), depending on whether  $\nu_\tau$  is stable or unstable on nucleosynthesis time scales ( $\sim 1 \text{ sec}$ ). An effectively stable  $\nu_\tau$  ( $\tau \geq 10 \text{ sec}$ ) in this mass range always increases  $Y$  relative to the standard case [57] (but, see [58]) and would thus make for a worse fit with the data. However, if  $\nu_\tau$  has a lifetime  $\lesssim 10 \text{ sec}$  and decays into  $\nu_\mu + \phi$  (where  $\phi$  is a ‘majoron-like’ scalar),<sup>3</sup> it is possible to decrease the predicted  $Y$  relative to the standard case (see figures 3 and 7 of Ref. [60]). Such an unstable  $\nu_\tau$  contributes less than a massless neutrino species at the epoch of BBN, thereby reducing the yield of  ${}^4\text{He}$ . For example, a  $\nu_\tau$  with mass  $20 - 30 \text{ MeV}$  which decays with a lifetime of  $\sim 0.1 \text{ sec}$  reduces  $N_\nu$  by  $\sim 0.5 - 1$  (and  $Y$  by  $\sim 0.006 - 0.013$ , respectively), thus helping to resolve the apparent conflict between theory and observation. It is also possible to alter the yield of BBN  ${}^4\text{He}$  by allowing  $\nu_e$  to be degenerate [61]. If there are more  $\nu_e$  than  $\bar{\nu}_e$ ,  $Y$  is reduced relative to the standard (no degeneracy) case as the extra  $\nu_e$ ’s drive the neutron-to-proton ratio to smaller values at freeze-out. A reduction of  $Y$  of  $\sim 0.01$  can be accomplished with a  $\nu_e$  chemical potential of  $\mu_e/T_\nu \sim 0.03$ , corresponding to a net lepton-to-photon ratio of 0.005. This is to be compared to the net baryon asymmetry which is smaller by  $\sim 7$  orders of magnitude. Nevertheless, scenarios for a large lepton asymmetry are possible [62]. Lastly, one can relax the assumption that baryons are homogeneously distributed. However,

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<sup>3</sup>Decays with  $\nu_e$  in the final state can directly alter the neutron-to-proton ratio and thus affect  $Y_{\text{P}}$  somewhat differently [59].

inhomogeneous BBN typically results in higher  $Y_{\text{P}}$ , and therefore does not naturally resolve the  $^4\text{He}$ -D conflict [63].

Provided that the high- $Y$ , low-D challenge can be resolved (by  $\Delta Y_{\text{sys}} \geq 0.011$  and/or  $N_{\nu} < 3$ ), low-D is consistent with the Pop II  $^7\text{Li}$  abundance if there has been a modest amount of lithium destruction/dilution in the oldest stars (see Figs. 1 and 5). The higher baryon density for low-D strengthens the case for dark baryons (see Fig. 9), although that for non-baryonic dark matter, while still very strong, is somewhat weakened. When folded with the hot gas bound on the x-ray cluster baryon fraction, a “cluster baryon crisis” persists, arguing for  $\Omega_{\text{M}} < 1$  (see Figs. 10–12).

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# TABLES

TABLE I. The constraints on  $\eta_{10}$ ,  $\Omega_{\text{B}}h^2$ ,  $N_{\nu}$ ,  ${}^4\text{He}$  mass fraction ( $Y$ ), and  ${}^7\text{Li}$  abundance from the high [12] and the combined ISM and low QSO-deuterium abundances [13,14,2] along with those from solar system D and  ${}^3\text{He}$  abundances [9]. The errors are for 68% C.L., while the ranges in the parentheses are for 95% C.L.

|   | High $\text{D}_{\text{QSO}}$         | Low $\text{D}_{\text{QSO}}$ & $\text{D}_{\text{ISM}}$ | $\text{D}_{\odot}$ , ${}^3\text{He}_{\odot}$ & BBN |
|---|--------------------------------------|---|--|
| Obs. $\text{D}/\text{H}$ ( $10^{-5}$ )  | $19 \pm 4$                           | $2.4 \pm 0.3 \pm 0.3, \geq 1.6 \pm 0.2$               | $2.6 \pm 0.9$                                      |
| $\eta_{10}$                             | $1.8 \pm 0.3$ (1.3 – 2.7)            | $6.4^{+0.9}_{-0.7}$ (5.1 – 8.2)                       | $5.0^{+1.5}_{-0.7}$ (3.5 – 7.9)                    |
| $\Omega_{\text{B}}h^2$                  | $0.007 \pm 0.001$<br>(0.005 – 0.010) | $0.023 \pm 0.003$<br>(0.019 – 0.030)                  | $0.018^{+0.005}_{-0.003}$<br>(0.013 – 0.029)       |
| $N_{\nu}$                               | $2.9 \pm 0.3$ ( $\leq 3.6$ )         | $1.9 \pm 0.3$ ( $\leq 2.4$ )                          | $2.1 \pm 0.3$ ( $\leq 2.6$ )                       |
| $Y$                                     | $0.234 \pm 0.002$<br>(0.231 – 0.239) | $0.249 \pm 0.001$<br>(0.246 – 0.252)                  | $0.247^{+0.003}_{-0.002}$<br>(0.243 – 0.251)       |
| ${}^7\text{Li}/\text{H}$ ( $10^{-10}$ ) | $1.5 \pm 0.6$ (0.7 – 3.0)            | $4.7 \pm 0.7$ (3.0 – 7.8)                             | $2.9^{+2.0}_{-0.8}$ (1.4 – 7.3)                    |

# FIGURES

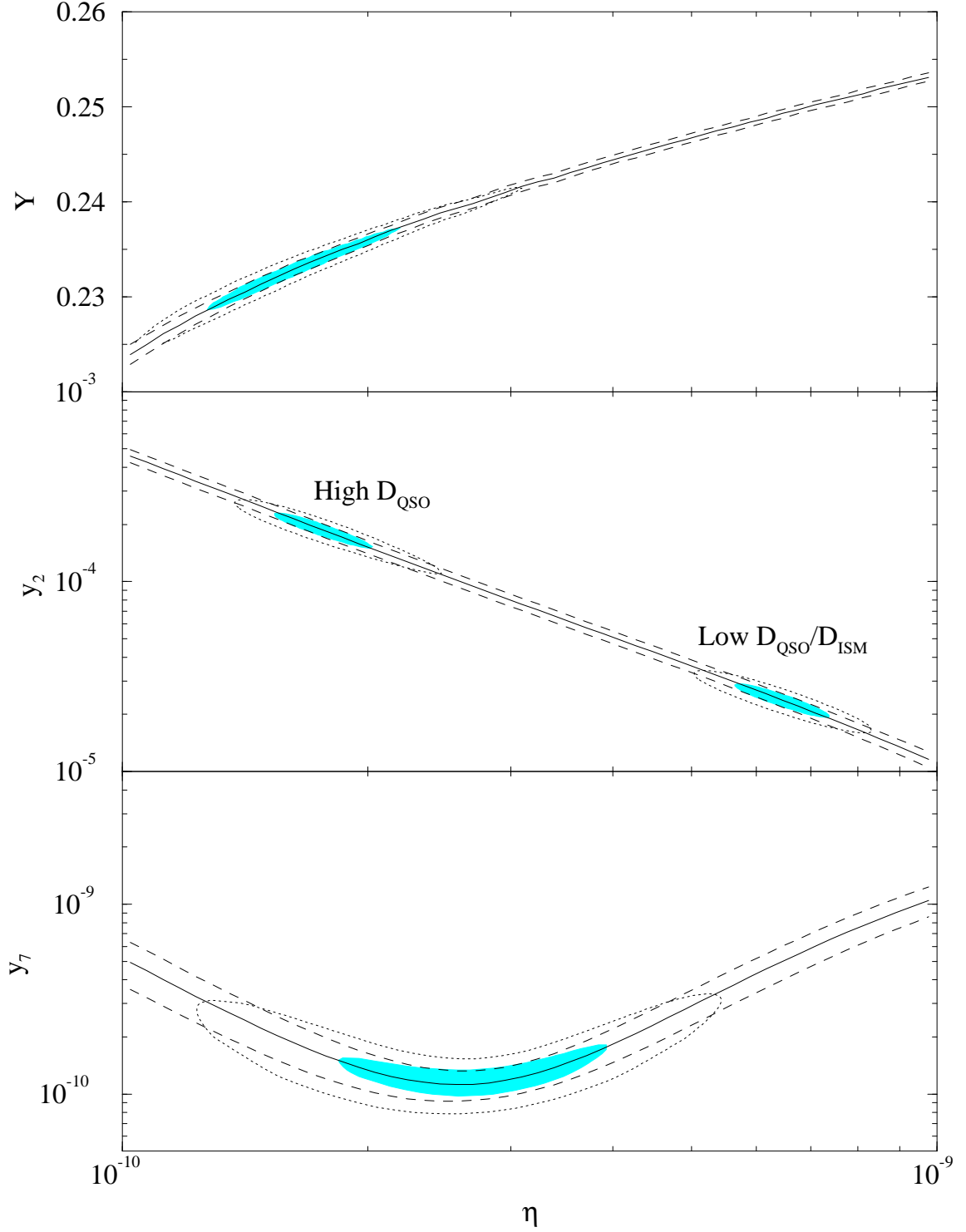


FIG. 1. BBN predictions (solid lines) for  $^4\text{He}$  ( $Y_{\text{P}}$ ), D ( $y_{2\text{P}}$ ), and  $^7\text{Li}$  ( $y_{7\text{P}}$ ) with the theoretical uncertainties ( $1\sigma$ ) estimated by the Monte Carlo method (dashed lines). Also shown are the regions constrained by the observations at 68% and 95% C.L. (shaded regions and dotted lines, respectively). We use the QSO measurements for  $y_{2\text{P}}$  from Ref. [12] and [13,14].

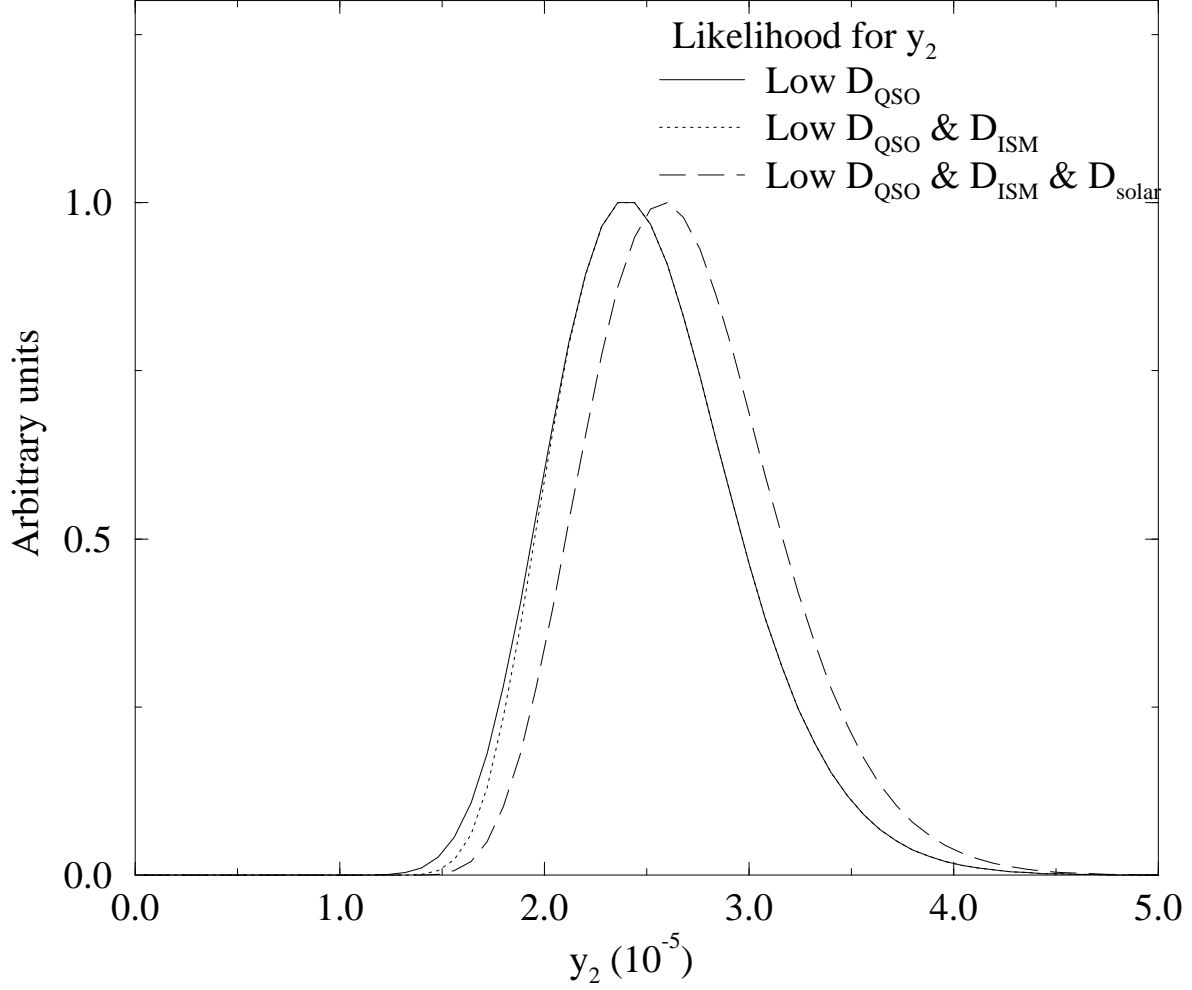


FIG. 2. The likelihood distributions for  $y_2$  implied by the low (QSO) D value (solid line) [13], the combined low D QSO and ISM limit (dotted line), and the combined limits from low D and ISM and solar system lower bounds (dashed line).

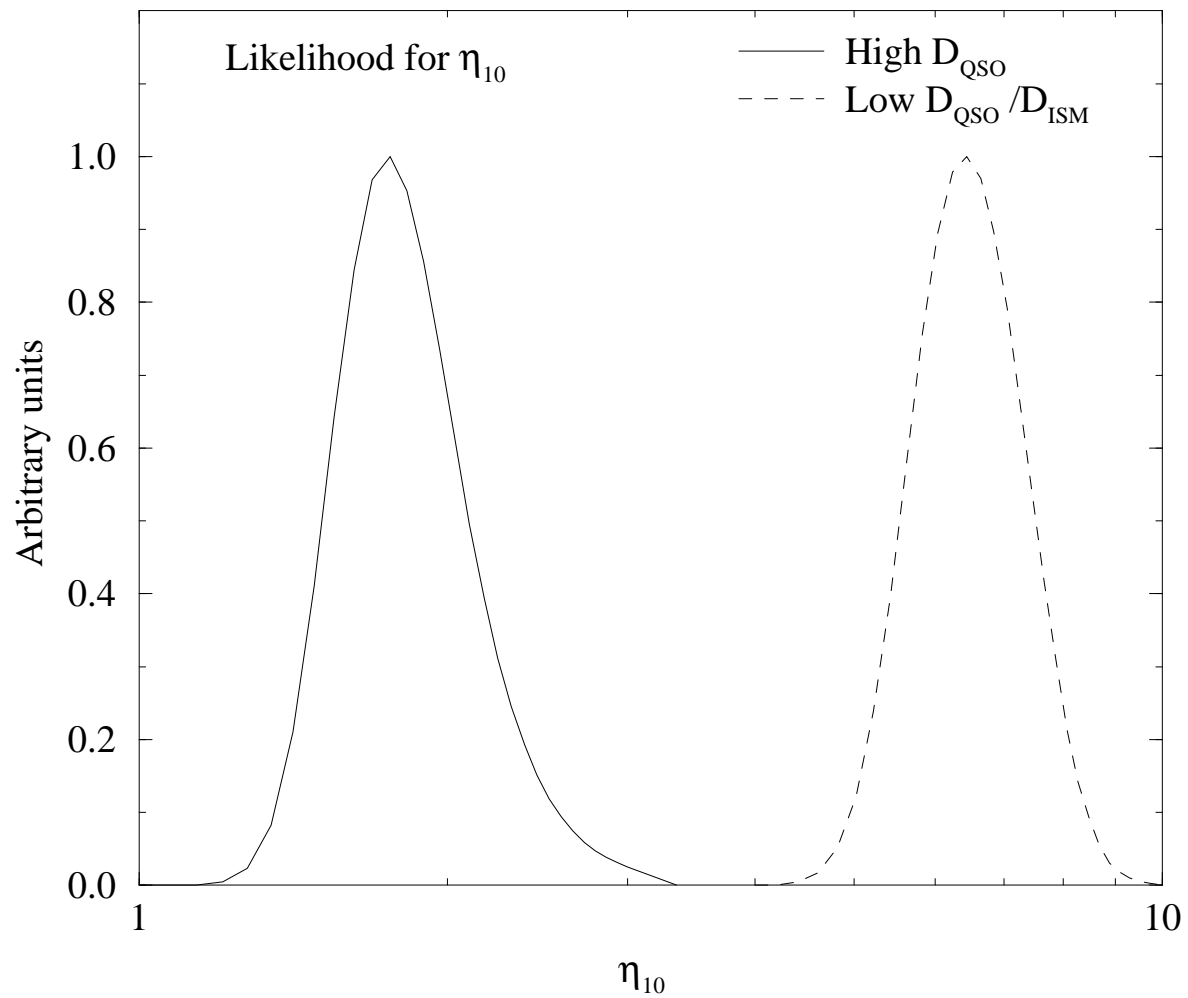


FIG. 3. The likelihood distributions for  $\eta_{10}$  implied by the high D value [12] and the low D (plus ISM) value [13,14].

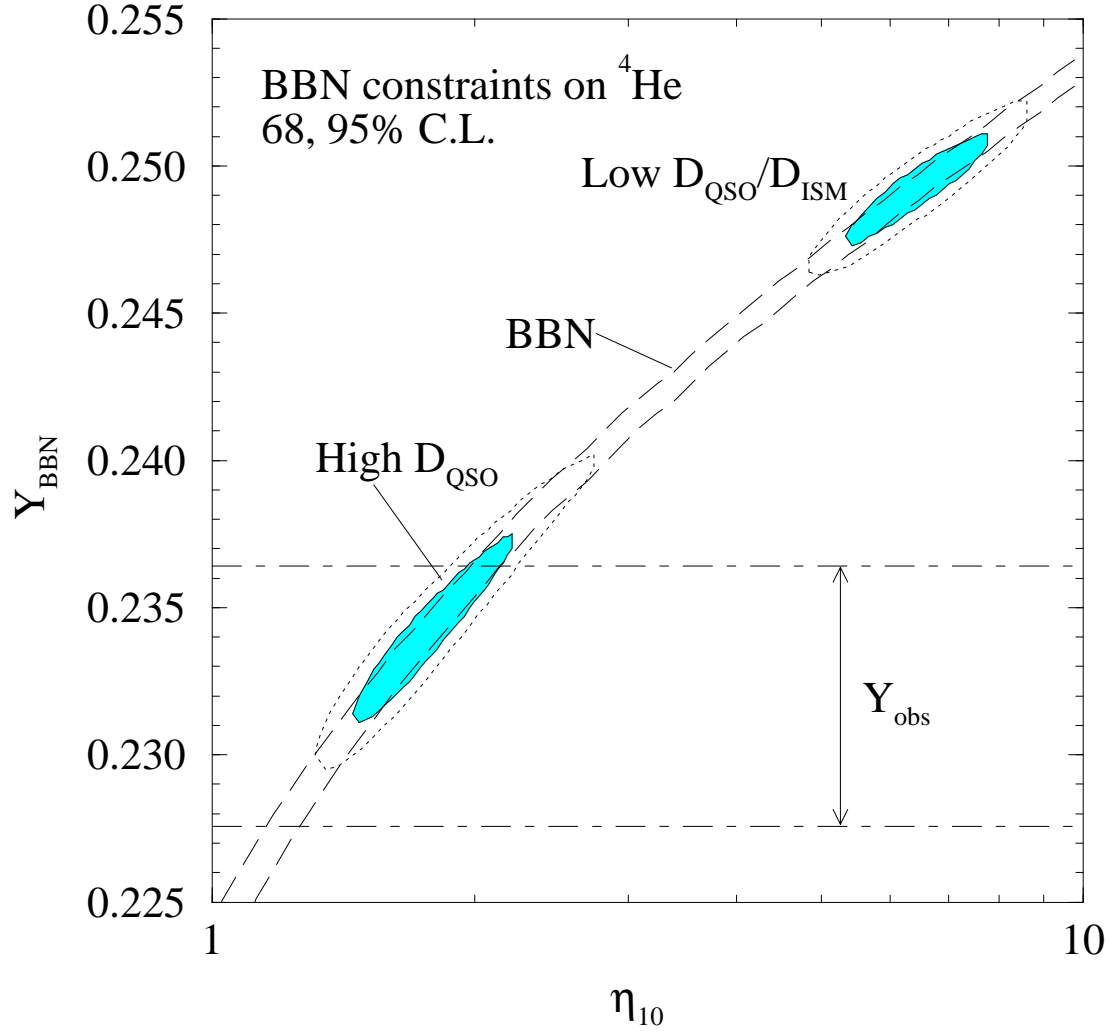


FIG. 4. The BBN prediction for the primordial  ${}^4\text{He}$  abundance implied by each of the two QSO  $D$  measurements. The shaded regions and the dotted lines correspond to the 68% and 95% C.L. constraints. The  ${}^4\text{He}$  abundance derived from HII region observations lies between the dot-dashed lines (68% C.L.)

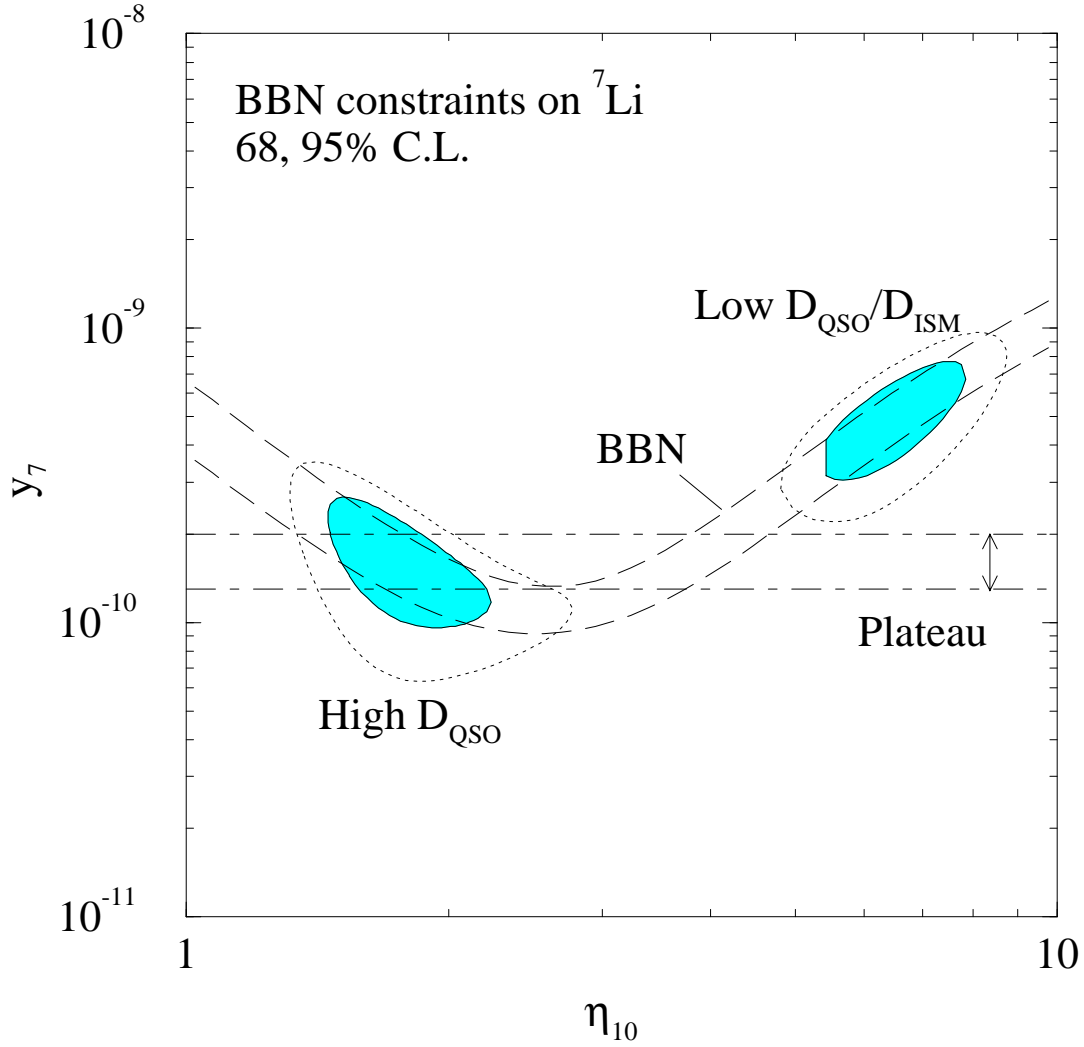


FIG. 5. The BBN prediction for the primordial  ${}^7\text{Li}$  abundance implied by each of the two QSO D measurements. The shaded regions and the dotted lines correspond to the 68% and 95% C.L. constraints. The plateau range (see text) derived from the stars in the galactic halo (ignoring depletions and creations) is indicated between the dot-dashed lines.

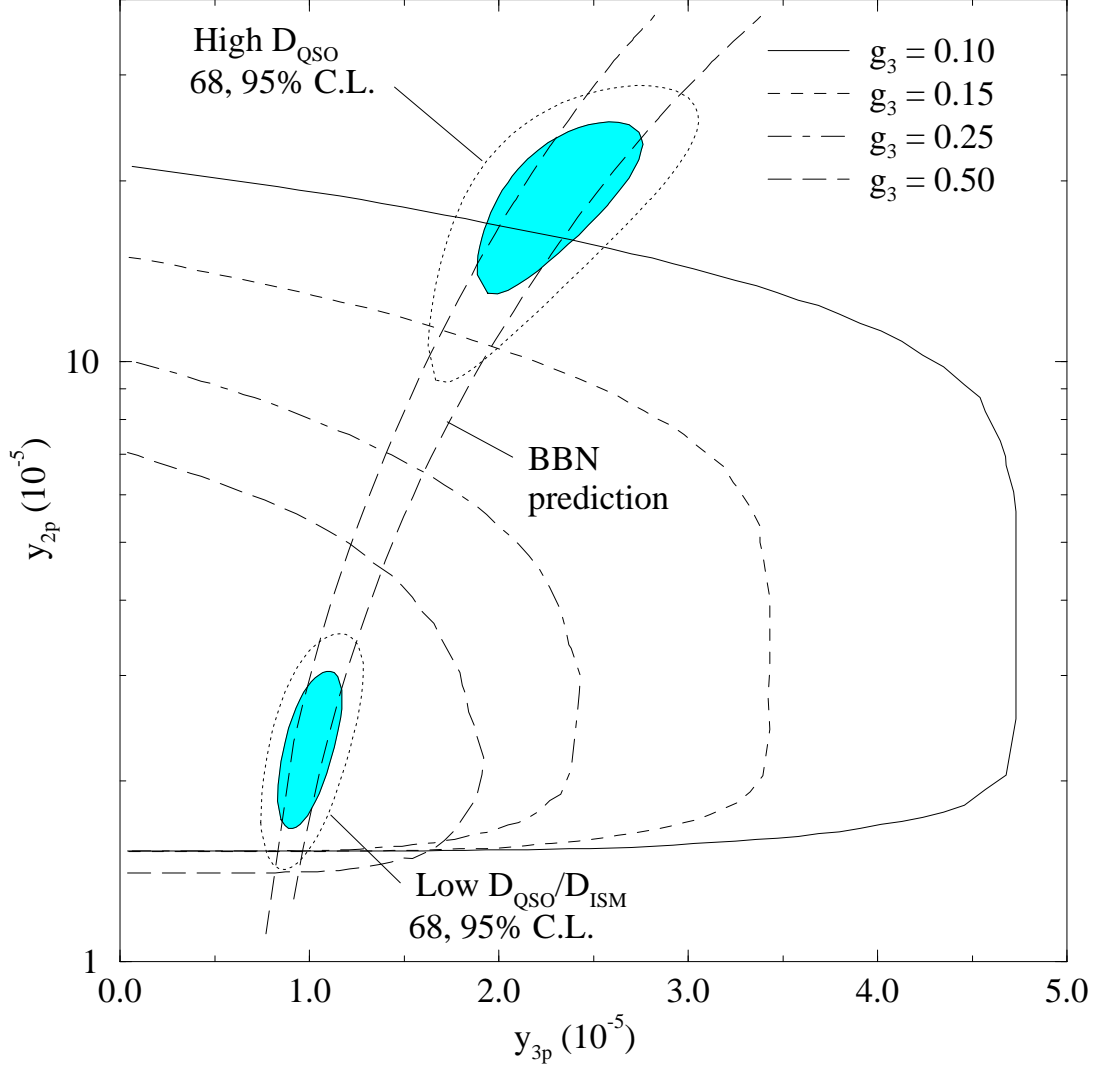


FIG. 6. The two QSO deuterium constraints, combined with the BBN prediction (long-dashed lines,  $1\sigma$ ), are shown in the  $y_{2p}$ - $y_{3p}$  plane (shaded regions at 68% C.L. and dotted lines at 95% C.L.). The regions inside the solid, dashed, dot-dashed, and long-dashed curves are the abundances consistent with the solar system data for  $g_3 = 0.10, 0.15, 0.25$ , and  $0.50$ , respectively [9].

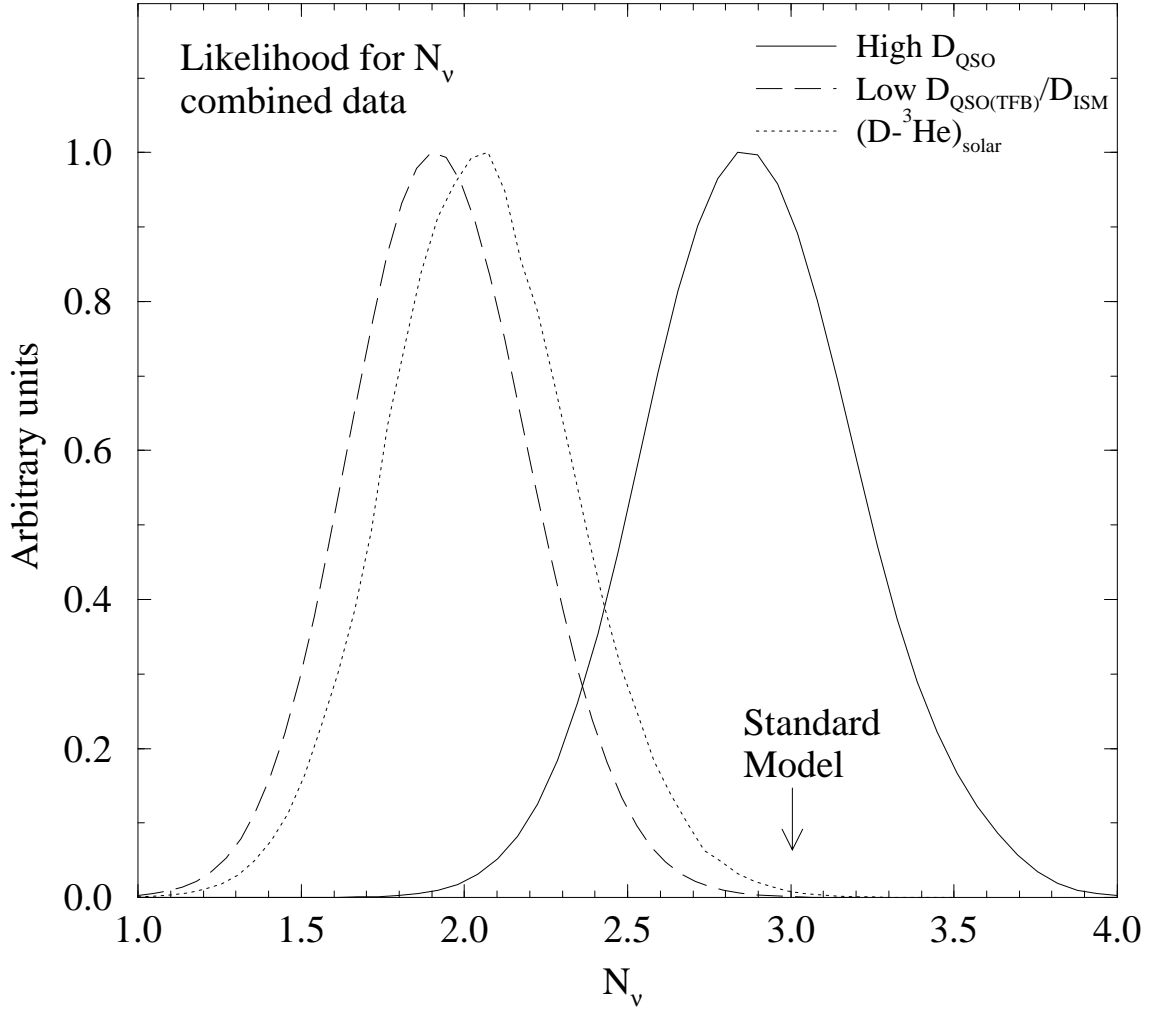


FIG. 7. The likelihood functions for  $N_v$  derived from the combined observations of D,  ${}^4\text{He}$ , and  ${}^7\text{Li}$ . The solid, dashed, and dotted curves are with high D, low D (QSO/ISM), and the solar D and  ${}^3\text{He}$  [9], respectively.



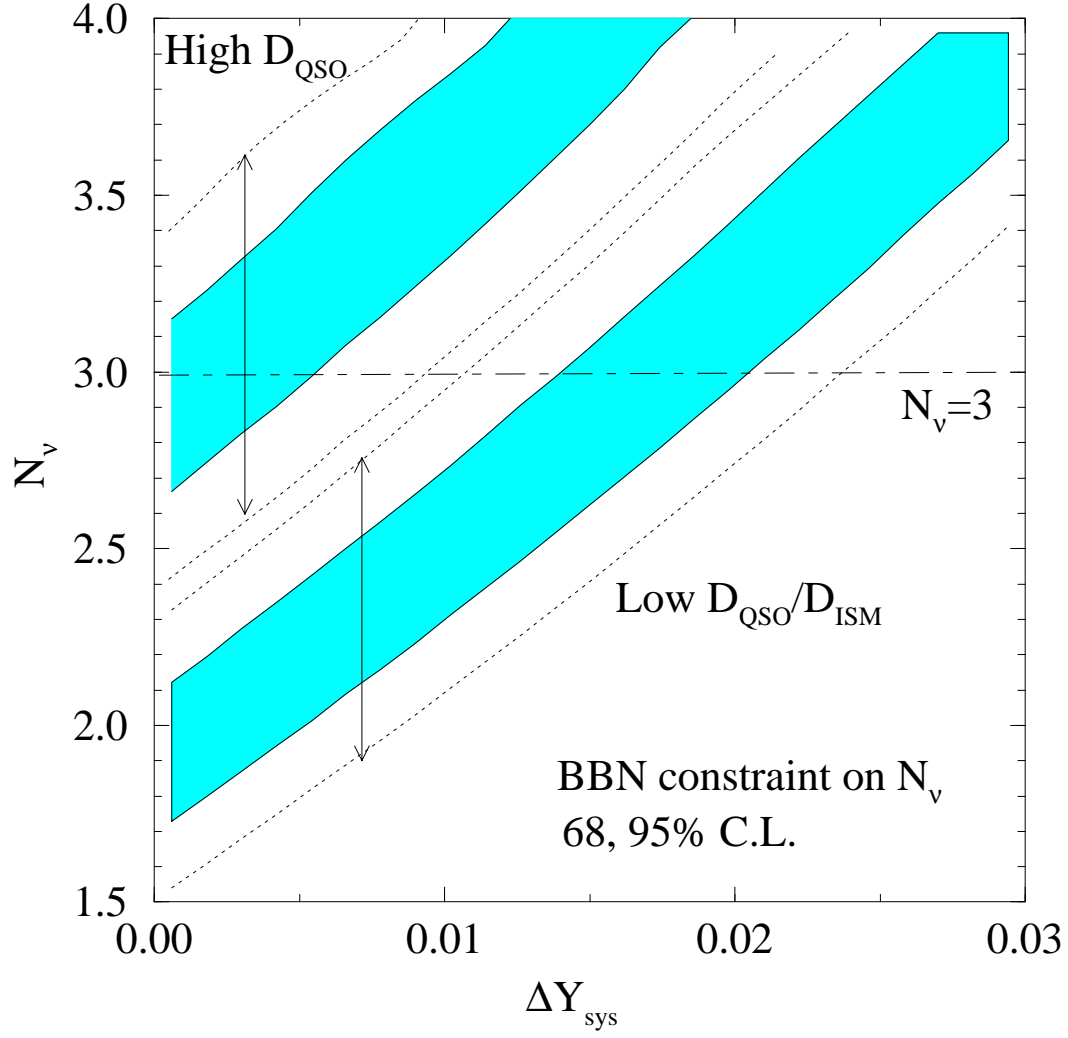


FIG. 8. The allowed range of  $N_\nu$  for high-D and low-D (QSO/ISM) as a function of systematic offsets ( $\Delta Y_{\text{sys}}$ ) in the  $^4\text{He}$  abundance derived from HII region data. The shaded regions (dotted lines) are for 68 (95)% C.L.

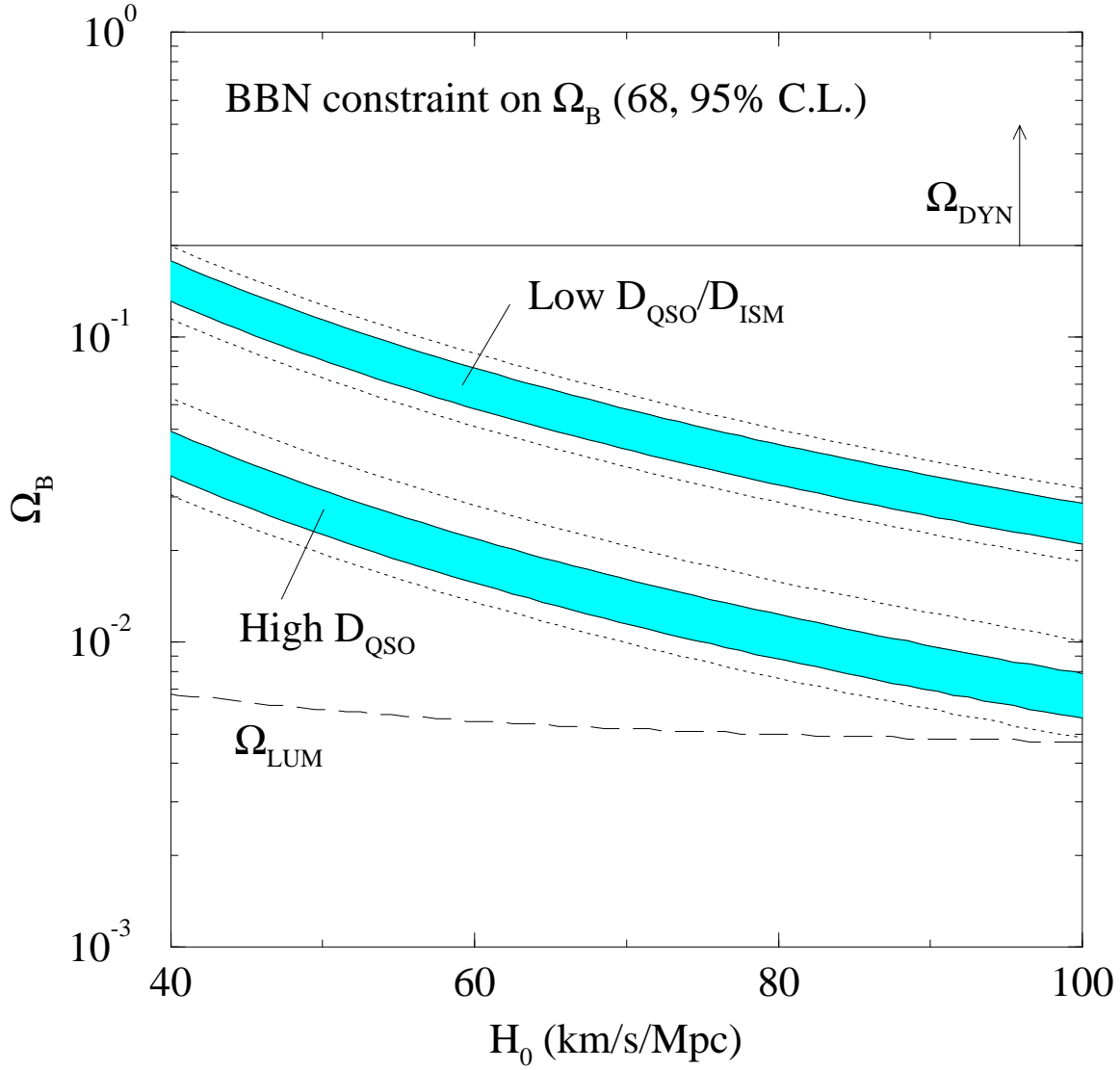


FIG. 9. The baryon density parameter  $\Omega_B$  versus the Hubble parameter  $H_0$ . The two bands correspond to the 68% (shaded) and 95% (dotted) C.L. ranges for  $\eta_{10}$  inferred from SBBN for high  $D_{\text{QSO}}$  and low  $D_{\text{QSO}}/D_{\text{ISM}}$  (see Table I). Also shown are the estimates [36] of the contributions to  $\Omega_B$  from luminous baryons in galaxies (dashed curve) and a dynamical estimate [37] of the lower bound to the total mass density parameter (solid line).

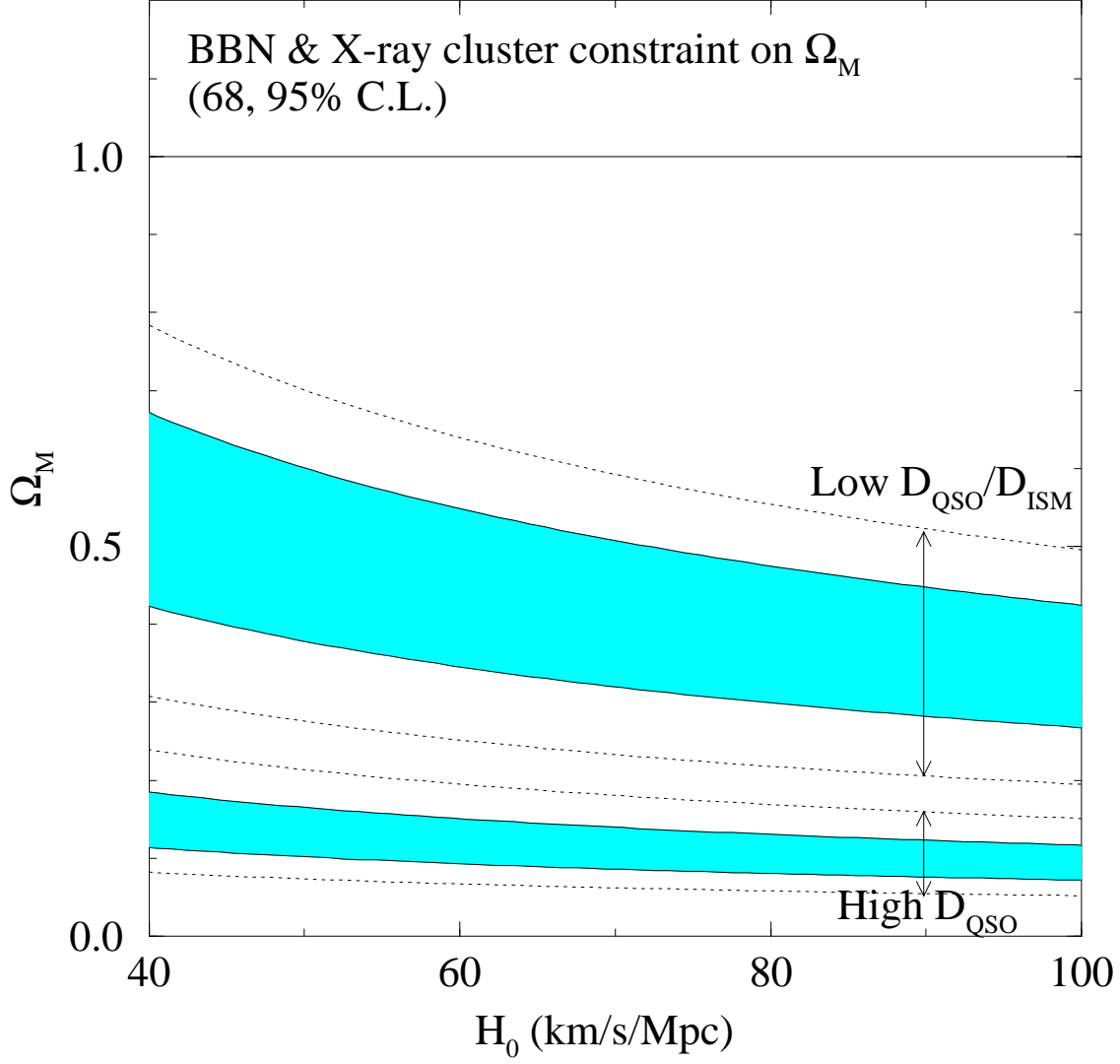


FIG. 10. BBN and x-ray cluster constraints on the total (matter) mass density parameter ( $\Omega_M$ ) versus the Hubble parameter ( $H_0$ ) for the two choices of primordial  $D$ . The shaded bands (dotted curves) are the 68% (95%) C.L. allowed regions (upper limits; see text).

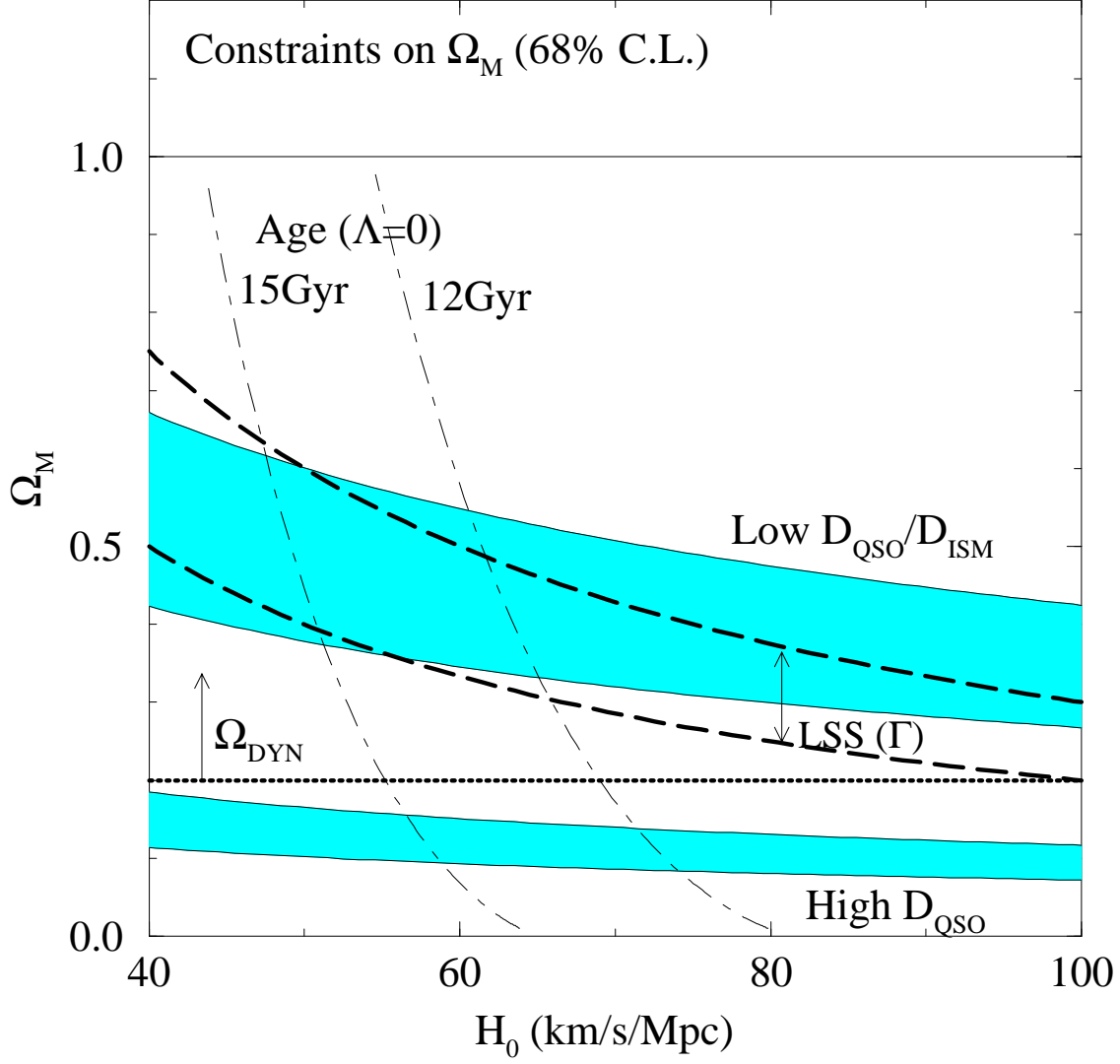


FIG. 11. The x-ray cluster constraints on the total mass density parameter ( $\Omega_M$ ) versus the Hubble parameter ( $H_0$ ) for high and low  $D$  (shaded bands, 68% C.L.) along with the constraints from the shape parameter  $\Gamma = \Omega_M h$  and the lower bound to  $\Omega_M$  from dynamics ( $\Omega_{\text{DYN}}$ ). Also shown are the  $\Omega_M$  vs.  $H_0$  relations for two choices of the present age of the universe.

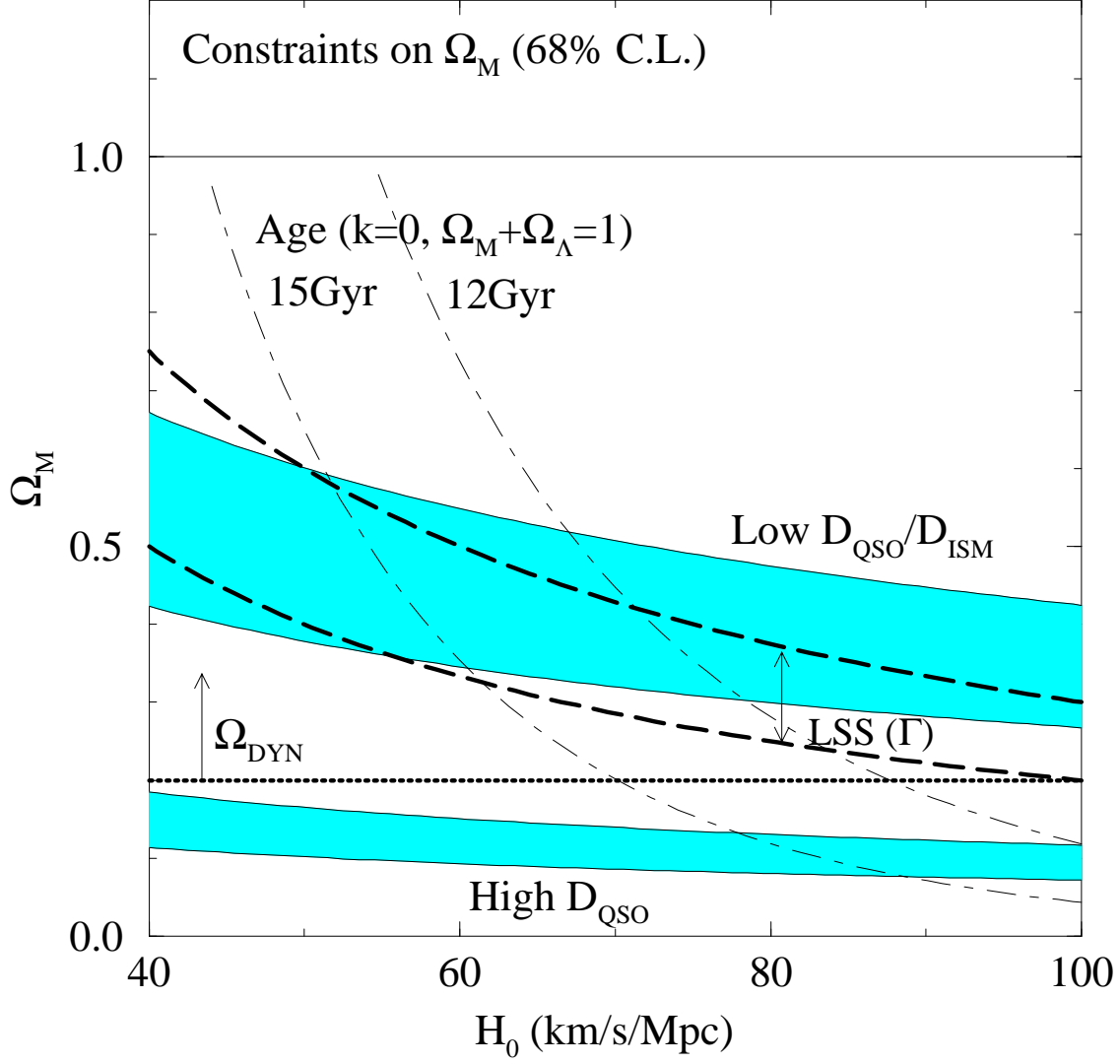


FIG. 12. As in Fig. 11, but for a zero curvature ( $k = 0$ ) model with  $\Lambda \neq 0$  ( $\Omega_M + \Omega_\Lambda = 1$ ).